

# Leptonic signatures for SUSY at the LHC

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**Abstract.** Most models of weak scale supersymmetry (SUSY) predict observable rates for production of SUSY matter at the CERN LHC. The SUSY collider events are expected to be rich in jets, isolated (and non-isolated) leptons and missing  $E_T$ . After first discussing the merits of mixed axion/axino vs. neutralino cold dark matter in SUSY models, I then survey prospects for detecting SUSY matter at the LHC via leptonic signatures. In the paradigm mSUGRA model, cascade decays of gluinos and squarks should yield high rates for multi-jet plus multi-lepton events, allowing values of  $m_{\tilde{g}} \sim 3$  (1.8) TeV to be probed for  $m_{\tilde{q}} \simeq m_{\tilde{g}}$  ( $m_{\tilde{q}} \gg m_{\tilde{g}}$ ) with  $100 \text{ fb}^{-1}$  of integrated luminosity. Direct production of gauginos and sleptons should also be possible in limited regions of parameter space. Even in the first year of LHC running, observable signals in multi-muon plus jets channel (without cutting on missing  $E_T$ ) can occur for interesting ranges of parameters. The highly motivated Yukawa unified SUSY models—where the dark matter is expected to be of mixed axion/axino type—should likely be testable in the first year of LHC running due to large rates for gluino pair production followed by cascade decays.

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## SUPERSYMMETRIC MODELS

Particle physics models including weak scale supersymmetry (SUSY) are highly motivated both from the theoretical as well as the experimental point of view[1]. On the theory side, SUSY stabilizes the Higgs sector, and allows one to extrapolate physics safely to very high energy scales. On the experimental side, the most impressive argument comes from extrapolating the measured values of the three Standard Model (SM) gauge couplings from the weak scale to the GUT scale. The celebrated unification of gauge couplings at  $M_{GUT} \simeq 2 \times 10^{16}$  GeV seems to indicate that 1. the Minimal Supersymmetric Standard Model (MSSM), or MSSM plus gauge singlets (or extra  $SU(5)$  multiplets), is the correct effective field theory all the way up to  $M_{GUT}$  and that 2. the unification certainly looks GUT-like, and that a SUSY GUT theory may be the correct effective field theory around  $Q \gtrsim M_{GUT}$ . Of the various GUT theories,  $SO(10)$  stands out in that it unifies not only the three SM forces, but also all the particles of each SM generation (into the 16 dimensional spinor of  $SO(10)$ ). In the simplest  $SO(10)$  SUSY GUT models, Yukawa couplings of the third generation are also expected to unify.

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There are a host of SUSY models which are consistent with gauge coupling unification. Some of them I list below:

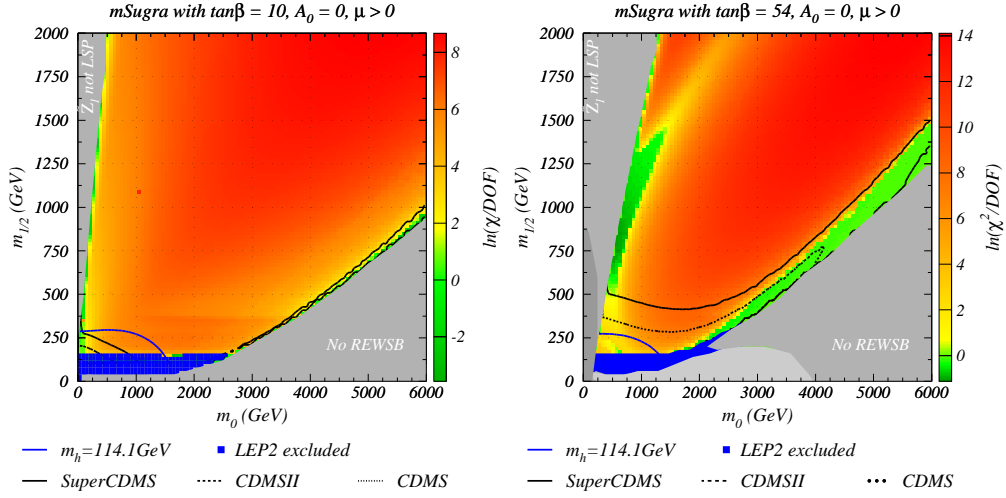
- gauge-mediated SUSY breaking (GMSB),
- anomaly-mediated SUSY breaking (AMSB),
  - mixed moduli-AMSB (mirage unification models)
  - hypercharged AMSB
  - deflected AMSB
- gravity-mediated SUSY breaking models[2],
  - mSUGRA (also known as CMSSM)
  - one and two parameter non-universal Higgs models (NUHM1,NUHM2),
  - non-universal gaugino masses in various guises
  - normal scalar mass hierarchy (broken generations) with  $m_0(1,2) > m_0(3)$ ,
  - compressed SUSY
  - split SUSY, pMSSM, NMSSM,
  - ...

Lately, gravity-mediated SUSY breaking models seem most popular because they can easily accommodate SUSY breaking via supergravity effects, and seem to most easily accommodate cold dark matter (CDM) in the universe. Of the gravity-mediated models, most work has been done on the mSUGRA (or CMSSM) model. Whether it is right or wrong, it is at least simple, consistent with all data, and exhibits many intriguing features which might be observable in the next round of collider and dark matter experiments. So most of the results I show will come from that model. At the end, I will comment on Yukawa-unified models, which only seem to occur when non-universality of soft SUSY breaking terms is allowed, as in the NUHM2 model.

## Neutralino vs. axion/axino cold dark matter

The lightest neutralino of SUSY, the  $\tilde{\chi}_1^0$  state, is a prototypical WIMP dark matter candidate[3]. The neutralino relic abundance can be calculated in SUSY models, and is embedded in public codes such as DarkSUSY, MicroMegas and IsaReD (the latter a part of the Isajet event generator). Several groups have been fitting the dark matter density,  $BF(b \rightarrow s\gamma)$ ,  $(g-2)_\mu$ , LEP2 constraints, plus possibly other EW observables, to SUSY models. I show here in Fig. 1 results from Balazs and I from 2003[4], since nothing of key importance has altered the situation since then.

The green regions show the good fit, and it is mainly governed by the fit to the WMAP-measured CDM density in the universe. Exhibited are 1. the stau co-annihilation region (left edge), 2. the hyperbolic branch/focus point (HB/FP) region (right edge), 3. the  $A$ -resonance annihilation region (at large  $\tan\beta$  only), and 4. a bit of the light Higgs  $h$ -resonance annihilation (at low  $m_{1/2}$ ) and 5. the so-called bulk annihilation region (at low  $m_0$  and low  $m_{1/2}$ , now largely excluded by LEP2). Most of the parameter space gives too much dark matter, and so is excluded. So much for the WIMP miracle! Neutralinos can make up the bulk of dark matter only under very fine-tuned conditions.



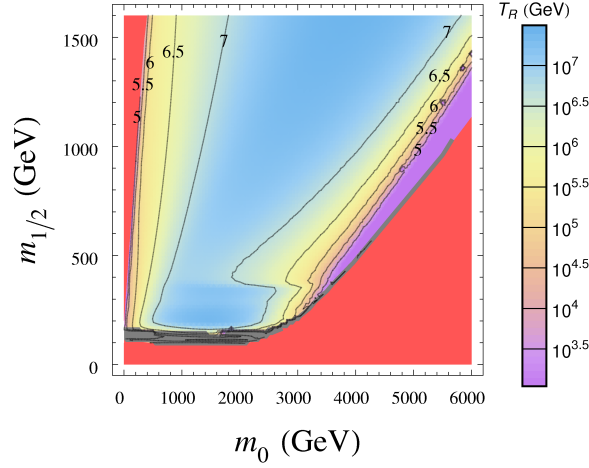
**FIGURE 1.**  $\chi^2$  fit of neutralino abundance,  $(g-2)_\mu$  and  $BF(b \rightarrow s\gamma)$  to SUSY parameters (in this case, using  $\tau$  data for hadronic vacuum polarization in  $(g-2)_\mu$ ).

SUGRA based models suffer another important constraint: the gravitino problem. Gravitinos can be produced at large rates in the early universe. If gravitinos are heavier than the other SUSY particles, then they decay into them with late-time decays, which can disrupt the successful predictions of Big Bang Nucleosynthesis (BBN). To avoid this[5], one must have, roughly, that  $m_{\tilde{G}} \gtrsim 5$  TeV or the re-heat temperature of the universe  $T_R \lesssim 10^5$  GeV (which conflicts with compelling baryogenesis scenarios like leptogenesis). One might try to avoid the gravitino problem by making the gravitino the lightest SUSY particle (LSP). But then thermal production of SUSY particles, followed by late-time decays to gravitinos, again disrupts BBN, unless (roughly)  $m_{\tilde{G}} \lesssim .1 - 1$  GeV[5].

In addition, another problem (that one neglects at one's peril) is the strong CP problem. The compelling solution here is the original Peccei-Quinn-Weinberg-Wilczek solution[6], which implies existence of an axion particle  $a$ . Cosmology constrains the PQ breaking scale  $10^8 \lesssim f_a/N \lesssim 10^{12}$  GeV, which means  $10^{-6} \lesssim m_a \lesssim 10^{-3}$  eV. Since we are in supersymmetry, the axion must be accompanied by a spin- $\frac{1}{2}$  super-partner the axino  $\tilde{a}$ [7]. The axino mass is relatively unconstrained: it can lie anywhere between the keV and multi-GeV range[8]. If  $m_{\tilde{a}} < m_{\tilde{\chi}_1^0}$ , then the  $\tilde{a}$  can be the LSP. In this case, dark matter can consist of a mixture of cold axions produced via vacuum mis-alignment[9], thermally produced axinos (whose abundance depends on  $T_R$ )[10], and non-thermally produced axinos arising from neutralino decay[8].

One can invoke the PQWW strong CP solution within the context of mSUGRA. In the case that the  $\tilde{\chi}_1^0$  is the lightest MSSM particle, then it will decay  $\tilde{\chi}_1^0 \rightarrow \tilde{a}\gamma$  (or possibly other modes) with a lifetime of order 1 second or less. Thus, it avoids the BBN problem (as long as  $\tilde{G}$  is heavy), but neutralinos will still give rise to  $E_T^{\text{miss}}$  at colliders.

For a given hypothesis of  $f_a/N$  and  $m_{\tilde{a}}$ , the WMAP-measured CDM abundance allows a calculation of  $T_R$ . Contours of  $T_R$  are shown in Fig. 2[11]. Everywhere in the plane



**FIGURE 2.** Contours of  $T_R$  needed to generate the WMAP measured CDM abundance using mixed axion/axino (but mainly axion) CDM in the mSUGRA model.

one gets the correct WMAP abundance. The blue regions have  $T_R > 10^7$  GeV, which at least allows for non-thermal leptogenesis[12]. The relevance of this plot for leptonic signatures at the LHC is that the entire LEP2-allowed parameter space of mSUGRA is also CDM-allowed, in the case of mixed axion/axino CDM: one should not focus just on the special neutralino DM-allowed regions for LHC SUSY signatures. Now on to leptonic LHC signatures!

## SLEPTON PAIR PRODUCTION

Direct production of sleptons can take place at LHC via the Drell-Yan mechanism:  $s$ -channel  $\gamma$  and  $Z$  exchange leads to  $\tilde{\ell}_L \tilde{\ell}_L^*$ ,  $\tilde{\ell}_R \tilde{\ell}_R^*$ ,  $\tilde{\nu}_\ell \tilde{\nu}_\ell^*$  production, while  $s$ -channel  $W$  exchange leads to  $\tilde{\ell} \tilde{\nu}_\ell$  production. The  $\tilde{\nu}_\ell$  may or may not decay to visible states. These reactions were investigated a long time ago[13], and the best signature was to look for  $\ell^+ \ell^- + E_T^{\text{miss}}$  final states arising from slepton pair production. Requiring  $p_T(\ell) > 40$  GeV,  $E_T^{\text{miss}} > 100$  GeV, a central jet veto and  $\delta\phi(\ell^+ \ell^-) < 90^\circ$  gave observable signals against  $W^+ W^-$ ,  $Z \rightarrow \tau^+ \tau^-$  and  $t\bar{t}$  backgrounds for  $m_{\tilde{\ell}} \lesssim 350$  GeV for  $10 \text{ fb}^{-1}$  of integrated luminosity at LHC with  $\sqrt{s} \sim 14$  TeV. Similar studies were performed by Denegri, Majerotto and Rurua[14].

## CLEAN TRILEPTONS FROM CHARGINO-NEUTRALINO PRODUCTION

A clean (jet-free) trilepton signature can arise from  $pp \rightarrow \tilde{\chi}_1 \tilde{\chi}_2^0 X$  production, followed by  $\tilde{\chi}_1 \rightarrow \ell \nu_\ell \tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0 \rightarrow \ell \bar{\ell} \tilde{\chi}_1^0$  decay[15]. In fact, this SUSY production cross section can be the dominant one at LHC in the case where squarks and sleptons have mass

greater than about a TeV. In the case of the clean  $3\ell + E_T^{\text{miss}}$  signal, we require each lepton to obey a “cone” isolation requirement to reject leptons arising from heavy flavor decay, and then require  $p_T(\ell) > 20, 20, 10$  GeV for the three hardest isolated leptons. We will also require a “central jet veto” (clean trileptons), and  $E_T^{\text{miss}}$  less than 100 GeV. Finally, require a leptonic Z veto to reject BG from WZ production. In this case, SM backgrounds are generally lower than SUSY signal in regions where the  $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$  branching fraction is substantial. It is substantial as long as other two body “spoiler” modes such as  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$  or  $\tilde{\chi}_1^0 Z$  are closed, or there is not large interference in the 3-body neutralino decay which suppresses the leptonic BFs. A virtue of this signal is that the dilepton pair from  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$  is kinematically constrained to obey  $m(\ell^+ \ell^-) < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$  (for 3-body decays) or a similar constraint if  $\tilde{\chi}_2^0 \rightarrow \ell^\pm \tilde{\ell}^\mp \rightarrow 3\ell$  occurs[16].

## GLUINO AND SQUARK CASCADE DECAYS TO MULTI-LEPTON PLUS JETS STATES

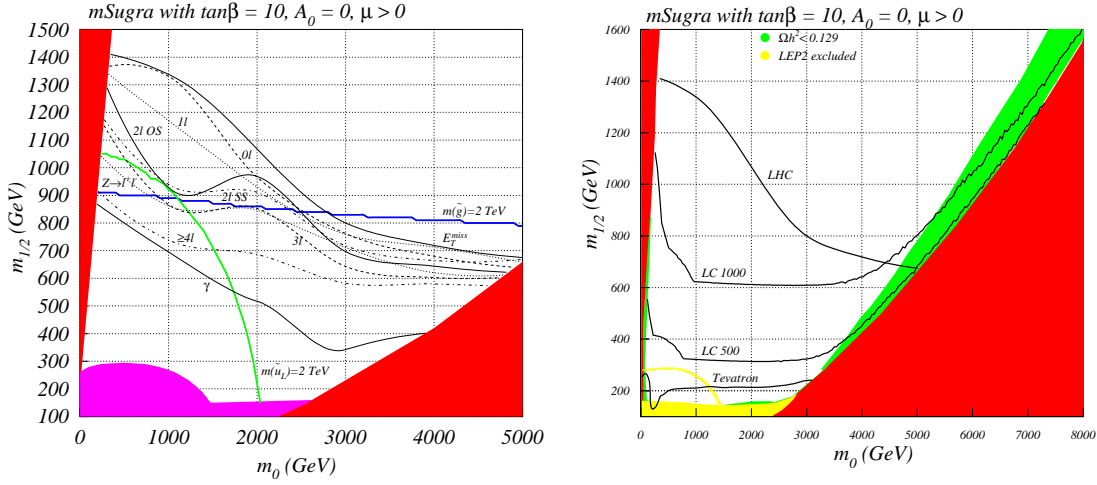
While slepton pair production and gaugino pair production can lead to clean multi-lepton events as LHC, we also expect multiple isolated lepton plus multijet plus  $E_T^{\text{miss}}$  events to arise from gluino and squark production[17]. The strong interaction processes  $pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q} + X$  are expected to be the dominant SUSY production modes at LHC as long as  $m_{\tilde{g}}, m_{\tilde{q}} \lesssim 1$  TeV.

The  $\tilde{g}$  and  $\tilde{q}$  states will then undergo “cascade decays”: possibly multi-step decay processes into SM particles plus the lighter superpartners until the state containing the LSP is reached. There are of order 1000 sparticle subprocess production reactions, and numerous decay modes of each sparticle, which are listed as output by programs such as IsaSUSY/IsaSUGRA, SUSYHIT and Sphenon. Thus, roughly  $10^5$  sparticle  $2 \rightarrow n$  reactions can occur at LHC in the case of the MSSM. The exact decay patterns are model dependent, and vary significantly around parameter space of any model. Generally, we expect gluino and squark cascade decay events to contain numerous high  $E_T$  jets (including numerous  $b$ -jets and possibly  $\tau$  jets, especially at large  $\tan\beta$ [18]), numerous isolated  $e$ s and  $\mu$ s and  $E_T^{\text{miss}}$ .

It is convenient to classify events according to the isolated leptons:

- $0\ell + E_T^{\text{miss}} + \text{jets}$
- $1\ell + E_T^{\text{miss}} + \text{jets}$
- opposite-sign (OS) dileptons  $+ E_T^{\text{miss}} + \text{jets}$
- same-sign (SS) dileptons  $+ E_T^{\text{miss}} + \text{jets}$
- $3\ell + E_T^{\text{miss}} + \text{jets},$
- $4\ell + E_T^{\text{miss}} + \text{jets},$
- $\dots$

One may simulate many thousands (millions) of signal events in SUSY model parameter space, and compare against SM BG rates (from  $t\bar{t}$ ,  $W + \text{jets}$ ,  $Z + \text{jets}$ ,  $VV$ , etc. ( $V = W, Z$  or  $\gamma$ )). For low mass SUSY particles, softer cuts work best, while for high mass SUSY, hard cuts are needed. Typically, we generate a large grid of cuts, and optimize over all



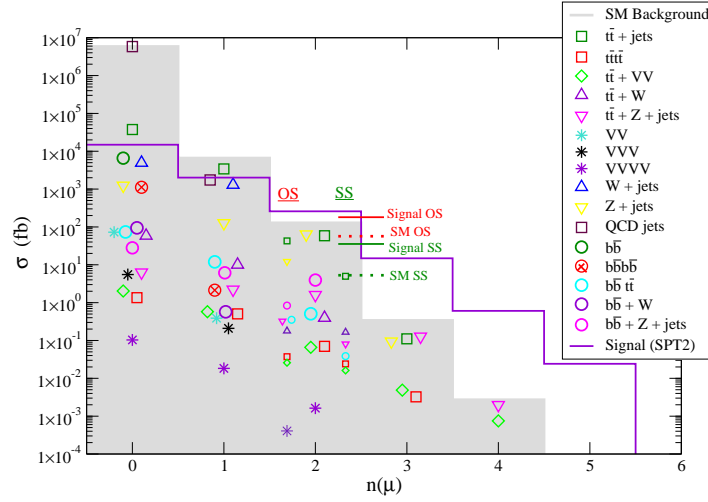
**FIGURE 3.** *a*). The reach of LHC for SUSY in various event topologies assuming  $100 \text{ fb}^{-1}$  in the mSUGRA model. *b*). The reach of LHC for SUSY for various colliders assuming  $100 \text{ fb}^{-1}$  at LHC and  $10 \text{ fb}^{-1}$  at Tevatron (in the mSUGRA model).

the various cut- channels. Then one may see where a  $5\sigma/10$  event signal is seeable for an assumed integrated luminosity. An example of the LHC SUSY reach in the  $m_0$  vs.  $m_{1/2}$  plane of the mSUGRA model is shown in Fig. 3a)., assuming  $100 \text{ fb}^{-1}$  of integrated luminosity. The furthest reach occurs in the  $0\ell + \text{jets}$  channel, and is  $m_{\tilde{g}} \sim 3 \text{ TeV}$  when  $m_{\tilde{q}} \simeq m_{\tilde{g}}$  (left side of plot), or  $m_{\tilde{g}} \simeq 1.8 \text{ TeV}$  for  $m_{\tilde{q}} \gg m_{\tilde{g}}$  (right side of plot)[19].

The LHC reach can be compared to the Tevatron reach (via clean trileptons), and an ILC reach for  $e^+e^-$  collisions at  $\sqrt{s} = 0.5$  and  $1 \text{ TeV}$  in Fig. 3b). Usually the LHC reach is dominant, except in the HB/FP region (right side of plots). In this region, squarks and possible gluinos are very heavy, and will be produced at low cross sections. However, since  $\mu$  is small, chargino production can occur at large rates at ILC, and these should be easily visible. However, over most of parameter space, LHC reach dominates. The main virtue of the ILC is that it can do high precision sparticle spectroscopy, while the LHC is somewhat more of a discovery machine (although it has good capability for sparticle mass reconstruction in regions where simple production and decay modes dominate)[16].

## EARLY DISCOVERY OF SUSY AT LHC VIA MULTI MUONS OR DIJETS

LHC is expected to turn on in November with  $pp$  collisions at  $\sqrt{s} \sim 7 \text{ TeV}$ , and to continue taking data for about a year. A common strategy is to first “re-discover” the SM, and once that is well understood, then begin the search for new physics. Theorists are an impatient bunch, however, and it is worth asking if early search and possible discovery of SUSY is possible during the first year of LHC running. Jets should be easily visible, although some energy calibration is necessary. Muons are easily identified, and in fact ATLAS and CMS have already seen millions of cosmic muons, which have been



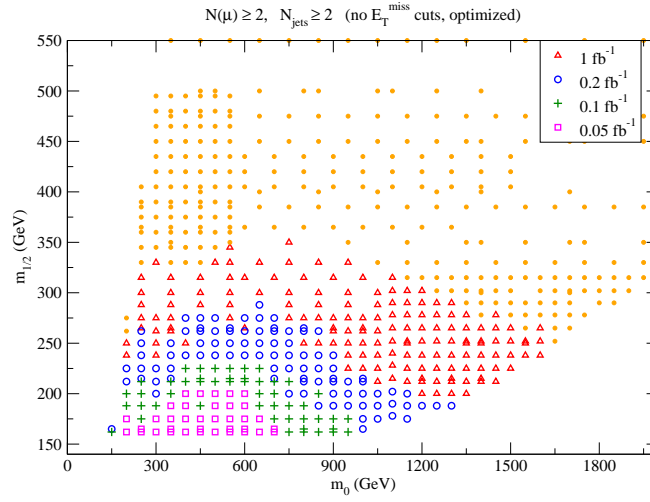
**FIGURE 4.** SUSY signal and SM BG for multi-muon plus  $\geq 4$  jets events at  $\sqrt{s} = 10$  TeV LHC.

used for alignment purposes. Electrons will be identifiable, although at first there may be a larger-than-desired  $e$ -jet differentiation problem. The hardest thing is to well-measure  $E_T^{\text{miss}}$  since  $E_T^{\text{miss}}$  is the negative of everything that is seen, and hence requires a *complete* knowledge of the detector. Indeed, experience from turning on the D0 detector shows that multi-bump  $E_T^{\text{miss}}$  spectra may be expected until the detector becomes well-known, and the data is cleaned up.

We examined if one can abandon the  $E_T^{\text{miss}}$  cut, and use some other cut to elicit SUSY signal from BG. The answer is *yes*, in the case of high isolated muon multiplicity[20, 21]. We plot event rate for multi-muon plus  $\geq 4$  jets events for signal (mSUGRA point (450,170,0,45,+1) purple histogram) and summed SM background (gray histogram) in Fig. 4. We see that SM BG dominates signal in the  $0\mu$  and  $1\mu$  channels. In the dimuon channel— for both OS and SS dimuons— signal now exceeds BG. In the trimuon channel, signal exceeds BG by a factor of about 20! And this is without any  $E_T^{\text{miss}}$  cut.

The LHC reach for  $\sqrt{s} = 10$  TeV in multi-muon plus  $\geq 4$  jets channel is shown in Fig. 5. Here, we see already some significant SUSY reach mainly in the OS dimuon channel for integrated luminosity as low as  $50\text{pb}^{-1}$ [21]! In the OS dimuon channel, in the favorable case, we expect production of  $\tilde{\chi}_2^0$  in gluino and squark cascade decays, followed by  $\tilde{\chi}_2^0 \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0$ . The dimuon mass distribution should build up a bump with kinematic cut-off sitting right in between the photon and Z poles. The signal should be readily apparent.

In addition to signals in the multi-mu plus jets channel, Randall and Tucker-Smith propose looking for SUSY in the dijets channel[22]— again without  $E_T^{\text{miss}}$ . Using judicious cuts, especially  $\Delta\phi(jj)$ , indeed SUSY signal stands out from QCD BG at low integrated luminosity! The reach in this channel is best at low  $m_0$ , where squark pair production occurs at large rates, leading to SUSY dijet events[21].



**FIGURE 5.** SUSY reach of LHC with  $\sqrt{s} = 10$  TeV for OS dimuons with optimized cuts for various low levels of integrated luminosity.

## PROSPECTS FOR YUKAWA UNIFIED SUSY AT LHC

Finally, let me address Yukawa-unified SUSY. At the beginning of this talk, I mentioned that SUSY GUT theories based on the gauge group  $SO(10)$  have a high degree of motivation in that they unify matter, in addition to unification of gauge couplings. The matter unification only works if one introduces a superfield  $\hat{N}_i^c$  ( $i = 1 - 3$  a generation index) containing a gauge singlet right hand neutrino state: exactly what is needed to give neutrinos mass and to explain neutrino oscillation data. In the simplest models, one also expects the Yukawa couplings of the third generation to unify at the GUT scale:  $t - b - \tau$  unification. A scan over parameter space of the mSUGRA model shows that such unification— which depends strongly on the  $t$ ,  $b$  and  $\tau$  masses, and on their weak scale threshold corrections— cannot occur[23]. At large  $\tan\beta \sim 50$ , they would like to unify, but radiative EWSB breaks down because the down-Higgs soft term runs more negative than the up-Higgs soft term. A way around this is to move to the NUHM2 model where  $m_{H_d}^2 > m_{H_u}^2$  at  $M_{GUT}$ , and neither is equal to  $m_0$ , the mSUGRA common scalar mass[24, 25, 26]. This is called “just-so” Higgs splitting (HS). One can also use  $SO(10)$   $D$ -term splitting, combined with generation splitting and inclusion of right-hand neutrino Yukawa coupling effects (the DR3 model[27]).

A scan over  $SO(10)$  model parameter space reveals that indeed in the HS or DR3 model, Yukawa unification can occur, but only for a very special range SUSY parameters leading to an inverted scalar mass hierarchy (IMH)[28]. The unification occurs if  $m_{16} \sim 10$  TeV, and  $m_{1/2}$  is as small as allowed by LEP2 experiments. Also,  $A_0^2 = 2m_{10}^2 = 4m_{16}^2$ . The specific parameter space leads to a specific sparticle mass spectrum, characterized by

- first/second generation squarks and sleptons  $\sim 10$  TeV,
- third generation scalars and heavy Higgs and  $\mu \sim 1$ -2 TeV,
- gluino mass  $\sim 300 - 500$  GeV



- light chargino  $\sim 100 - 180$  GeV
- a bino-like  $\tilde{\chi}_1^0$  with  $m_{\tilde{\chi}_1^0} \sim 50 - 80$  GeV.

The model is very compelling, except that it predicts a neutralino relic abundance of around  $10^2 - 10^4$  times that measured by WMAP. So it is excluded? No. Here, we invoke the PQWW solution to the strong CP problem, with an axino mass  $\sim$  MeV scale. Then the  $\tilde{\chi}_1^0 \rightarrow \tilde{a}\gamma$  decay reduces the relic abundance by a factor of  $10^3 - 10^5$ ! The cosmology was investigated in Ref. [29], and works best if dark matter is composed of mainly cold axions, with a small contribution of thermal and non-thermal axinos. We expect the gravitino mass  $m_{\tilde{G}} \sim m_{16} \sim 10$  TeV, which means the gravitino decays before the onset of BBN, so the gravitino problem is solved. In addition, the model allows a re-heat temperature  $T_R \sim 10^7$  GeV: enough to sustain at least non-thermal leptogenesis (wherein the heavy right-hand neutrino states are produced via inflaton decay).

The whole scenario is very compelling, but how do we test it? Well, the rather light gluinos mean gluino pairs will be produced at high rates at the LHC, and may even yield signals during the first year of running in the multi-mu plus jets channel, or multi- $b$ -jet channel[30]. The dimuon spectrum should exhibit the characteristic mass edge around  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim 50 - 80$  GeV. Also, the prediction is that there will be no signals in any direct or indirect WIMP search channels. However, the ADMX experiment stands a good chance of finding an axion signal in their cryogenic microwave cavity experiment[31].

## CONCLUSIONS

I present my conclusions as a bullet list.

- In many gravity mediated models, such as mSUGRA, the axion/axino mixture is (IMO) a better candidate for CDM than neutralinos. If so, then entirely different regions of model parameter space are preferred.
- Direct production of slepton pairs can be searched for at LHC up to  $m_{\tilde{\ell}} \sim 350$  GeV for  $\sim 10 \text{ fb}^{-1}$  of integrated luminosity.
- Clean trileptons from  $\tilde{\chi}_1 \tilde{\chi}_2^0$  production should be visible unless  $\tilde{\chi}_2^0$  spoiler modes open up (or large interferences occur in 3-body decays).
- Multi-lepton plus multi-jet +  $E_T^{\text{miss}}$  events offer the best LHC reach for SUSY: for  $100 \text{ fb}^{-1}$ ,  $m_{\tilde{g}} \sim 1.8 - 3$  TeV can be probed, depending on  $m_{\tilde{q}}$ .
- It is possible to perform an early search for SUSY in multi-mu plus jets *without*  $E_T^{\text{miss}}$  channel (or dijet channel) even with very low integrated luminosity.
- Yukawa unified SUSY has a very characteristic spectrum with light gluinos and heavy squarks. It gives robust signatures at LHC in the first year of running. It is cosmologically viable if the dark matter is composed of an axion axino admixture (but with mainly axions).

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